Target Discrimination in Polarimetric ISAR Data using Robust Feature Vectors

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Abstract

We study the robustness of features against aspect variability and target modification for the purpose of target discrimination using polarimetric 35 Ghz ISAR data. The data are obtained with the MEMPHIS radar and comprise ISAR data of 16 targets providing imagery at a resolution of about 20 cm resolution for a complete aspect angle range of 360 degrees. The data cover three classes of military targets (T72, ZSU and BMP) with several modifications. For the study we have composed feature vectors out of individual radiometric, geometric and polarimetric features extracted from the imagery. Using the feature vectors and a nearest neighbour classifier we have determined how well different targets classes and different target modifications can be separated. We have found that good discrimination results are obtained between the target classes but that no discrimination is obtained between the different modifications.

1. Introduction

With the increasing use of UAVs for RSTA purposes also the interest in SAR imaging systems is growing, because of their unparalleled all-time and all-weather capability. In this context a study for the Dutch MOD was defined in which the role of SAR for ground surveillance is investigated. This study is carried out within the framework of the NATO/SET069 research group, which focuses on robust acquisition of relocatable targets with advanced millimetre wave techniques. By participating in the group we have access to a database with high resolution SAR and ISAR data for various targets and scenes. This database was created and is maintained by the group to study automatic target recognition techniques in the millimetre wave domain. FGAN-FHR has contributed to the database with high-resolution (20cm) ISAR data of three military targets at 35 Ghz showing various modifications. These data comprised a main battle tank (T72) an air defence unit (ZSU23-4) and an infantry-fighting vehicle (BMP2).

We have used these data for studying features, which are able to discriminate targets in high resolution SAR data. The study presented here focuses on the robustness of features against aspect angle variability and target modification.

In the paper we first describe the data, introduce the feature used in this paper and present a method for aspect angle determination. In the following section firstly we analyse the features independently and secondly we analyse the features by combining them into feature vectors and by considering aspect angle intervals. Finally we summarise and give conclusions.

2. Description of data

The ISAR data have been obtained using the polarimetric MEMPHIS radar located on top of a 47 meter high tower. The three targets (T72, ZSU 23-4 and BMP) were positioned on a turntable at a distance of about 154 meter, giving rise to a slant range of 161 meter and a depression angle of 17°. The MEMPHIS 35 GHz radar transmitted linear V polarisation, and received H and V simultaneously thus providing orthogonal VV and VH channels. The ISAR data comprise about 36000 range lines for about 360 degrees of aspect angle and 256 frequency steps covering 640 Mhz. For more information we refer to Schimpf (2004). The

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original target set consisted of 17 measurements of the three targets with several modifications for each target. We have discarded one measurement, which did not cover the complete 360 degrees of aspect (target T72e, Schimpf 2004). All measurements started at about 0 degrees of aspect, except for target ZSU23-4b, which started at an aspect angle of 14 degrees. The following table gives an overview of the data used where the naming convention is following Schimpf 2004.

Table 1 Target measurements used in the study

Target ID	Modification	No. of range lines
T-72a	Gun –20° azimuth (left)	36963
T-72b	Gun 0° azimuth (forward)	37001
T-72c	Gun 30° azimuth (right)	36876
T-72d	Gun 60° azimuth (right)	36963
T-72f	Gun 120° azimuth (right)	37001
T-72g	Gun 150° azimuth (right)	37001
T-72h	Gun 180° azimuth (backward)	37013
ZSU 23-4a	driver’s hatch closed, commander’s hatch closed	36013
ZSU 23-4b	driver’s hatch open, commander’s hatch closed	35762
ZSU 23-4c	all hatches open	36013
ZSU 23-4d	driver’s hatch closed, commander’s hatch open	36013
BMPa	All hatches closed	37375
BMPb	driver’s hatch open, commander’s hatch closed	37375
BMPc	driver’s hatch open, commander’s hatch open	37375
BMPd	driver’s hatch open, commander’s hatch open, turret hatch open	37375
BMPe	driver’s hatch closed, commander’s hatch open, turret hatch open	37375

The measured data are in the frequency domain and spatial domain imagery is obtained through a 2-D inverse FFT (Chen and Andrews 1980) for 128 range lines and 256 frequency steps. Hamming weighting was applied to reduce the sidelobes of the impulse response. The resulting resolutions are therefore about 24 cm in range and 20 cm in cross-range (aspect). Images have been obtained both for VV and VH polarisation. We show in figure 1 an example for each target class (VV polarisation). In order to obtain features as a function of aspect angle we have calculated 360 images for every degrees of aspect from the data.

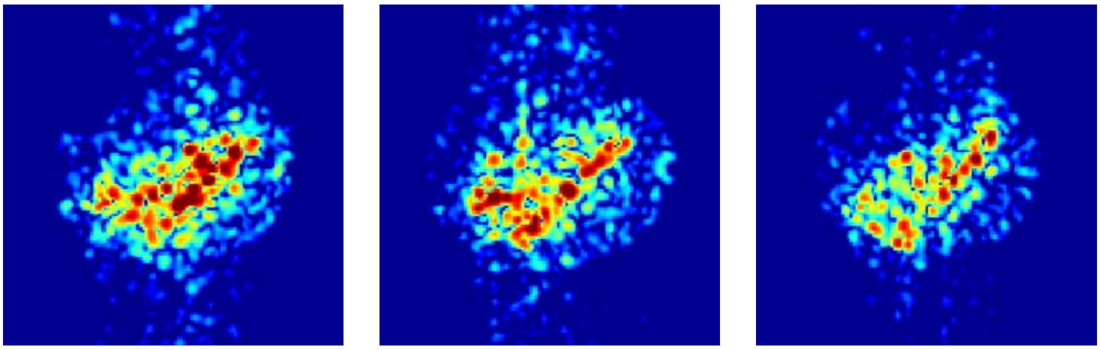

Figure 1. Images of the targets. Left T72b, middle ZSU23-4a and right BMPa

3. Description of features

We introduce a set of features, which have been defined within the NATO/SET069 working group (Dekker and van den Broek, 2000) and which will be analysed for robustness against aspect angle and modification. We discriminate between three categories of features: radiometric, geometric and polarimetric. Table 2 summarises the features used.

Table 2. Overview of features used

Type	Feature	Description
Radiometric	*MEAN*	mean intensity
	CVAR	coefficient of variation
	WFR	weighted rank fill ratio
Geometric	*AREA*	area of target
	NN	neighbour number
	LAC	lacunarity index
	LEN	length of target
	WID	Width of target
Polarimetric	*VVVH*	polarimetric (VV/VH) power ratio

As a basis to calculate the feature values we used a CFAR detector (Novak and Hesse, 1991) to detect target pixels. To obtain so-called CFAR masks we used dB scaled imagery and the CFAR constant was chosen at an average backscatter level of the pixels in the target area in dB scaled VV polarised images. In this way CFAR mask covers the pixels with stronger scattering from the target and almost no background pixels. Figure 2 shows an example of a CFAR mask.

Below we give a short description of the features.

MEAN: The mean of the power in dB of the detected target pixels, which indicates how bright the target appears in the image.

CVAR: The normalized variance of the power of the detected target pixels indicates how smooth or not the scattering is distributed over the target and is defined by the ratio of the standard deviation over the mean of the power of the detected target pixels

WFR: This measure is defined as the ratio of the sum of the power of the *N* brightest pixels, and the sum of power of all detected pixels (Kreithen et al. 1993). This feature measures the relative amount of scattering due to 'hot spots'. The choice for N depends on the resolution of the images, since this the resolution determines the number of pixels, which cover the target. In this case (20-24 cm resolution) we took N=20.

AREA: The number of detected target pixels. This feature clearly indicates the geometric extent of the target.

NN: The neighbour number is a measure for the spatial distribution of the CFAR detected target pixels (van den Broek et al., 2001). The number is defined by total number of neighbour pixels of all detected pixels normalized by the total number of detected pixels. This feature is a kind of texture measure indicating how well detected pixels are lumped together.

LAC: The lacunarity index is a textural feature that can discriminate between differently appearing surfaces with the same fractal dimension. It is calculated by counting the number of detected pixels within an $n \times n$ moving window (we use here n=3). For the resulting moving-widow filtered image the coefficient of variation is calculated, only for non-zero values of the

detected pixels. This figure gives the lacunarity index and is a measure of the variation in lumpiness of the detected pixels. In other words the feature measures whether the detected pixels form a regular pattern (low value) or an irregular pattern (high value). Obviously, this feature only gives significant information when enough pixels are detected and the resolution is high enough.

LEN: The extent of the detected target pixels along the long axis of the target. The direction of the long axis is obtained after aspect angle determination (see following section).

WID: The extent of the detected target pixels along the short axis of the target. The direction of the short axis is obtained after aspect angle determination (see following section).

VVVH: This polarimetric measure is defined as the ratio of total powers in dB from the detected pixels in the VH image and the VV image. Note that the pixels are detected using the VV image.

4. Aspect angle determination

Aspect angle determination is important to be able to calculate features like width and length of a target. Also important is that the robustness of features has to be valid only for smaller aspect intervals if the aspect angle can be measured with sufficient accuracy. To determine the aspect angle we have used Radon transformation of an image (the Radon transform). The Radon transformation of an image *f(x,y)* is defined as

$$g(\rho,\theta) = \int\int f(x,y)\delta(\rho - x\cos\theta - y\sin\theta)dxdy\,, \qquad (1)$$

where δ denotes the Dirac delta function, θ is the rotation angle and ρ is the spatial axis parameter. Ideally a target in an image can be considered as a rectangular shape. The Radon transformation of an image containing such a shape will show a band, with peaks at the angle, for which the rectangle is seen along its long axis. Determination of the maximum in the Radon transformation image therefore gives the aspect angle. This method works well when the target box is homogeneous. We have therefore used the CFAR mask (see figure 2).

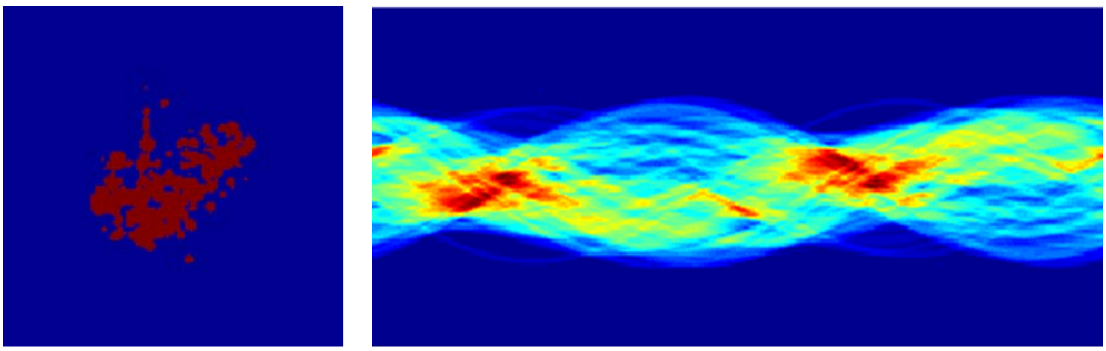

Figure 2. Left CFAR mask for ZSU23-4 target. Right its Radon transform

Note that with this method of aspect angle determination we cannot make distinction between head and rear of the targets. The values therefore are always between 0 and 180 degrees. In figure 3 we have plotted the values found against the actual values for the T72b target and the ZSU23-4b target.

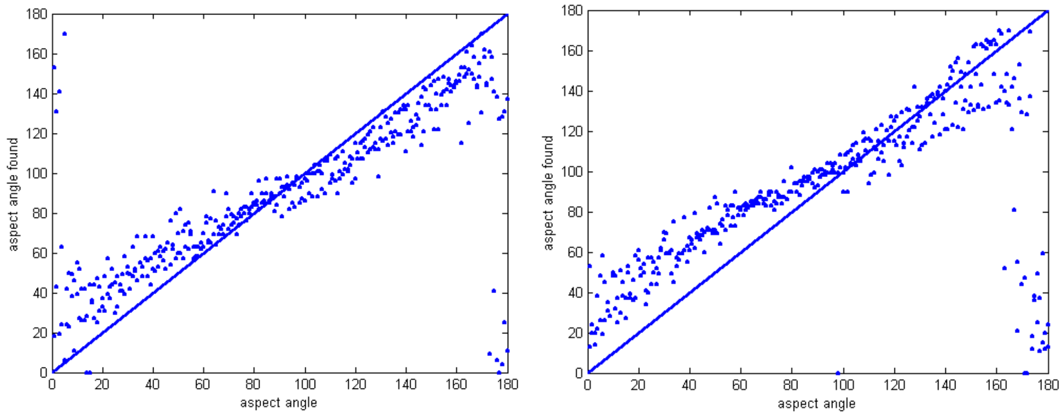

Figure 3. Aspect angle found using the Radon transform against the expected aspect angles for the T72b target (left) and the ZSU23-4b target (right).

In figure 7 the solid line indicates the expected aspect angle. The figure shows that on average the aspect angle can be determined with an accuracy of about 20 degrees. The determined values have an offset from the expectation between 0 and 90 degrees and also between 90 and 180 degrees in opposite direction. This may be due to the fact that the CFAR mask is also filled in the middle, so that the maximum does not correspond to the long axis but to the diagonal of the target box. Note that the average shift of the values from the solid line in the figure for ZSU23-4b confirms the starting aspect angle of 10 degrees (see previous section).

5. Analysis of robustness

The goal of this paper is to study the robustness of features. This implies that in the optimal case such features can characterise a target irrespective of aspect angle or target modification. Whether such features are able to discriminate between targets is another issue and depend on the targets. For example the length of a feature should in principle be a robust feature against aspect angle, since change of aspect angle should not change the length. Whether such a feature can discriminate between targets obviously depend on the difference in length between the targets. Firstly we will analyse the features individually and secondly when they are combined into feature vectors.

5.1 Individual features

In order to check the robustness against aspect angle we use features for the so-called ‘basic’ target modes (i.e. without modification) for which we choose targets T72b, ZSU23-4a and BMPa. In figure 4 we show for each feature category an example (MEAN, LEN and VVVH) as a function of aspect angle and in figure 5 the corresponding distributions.

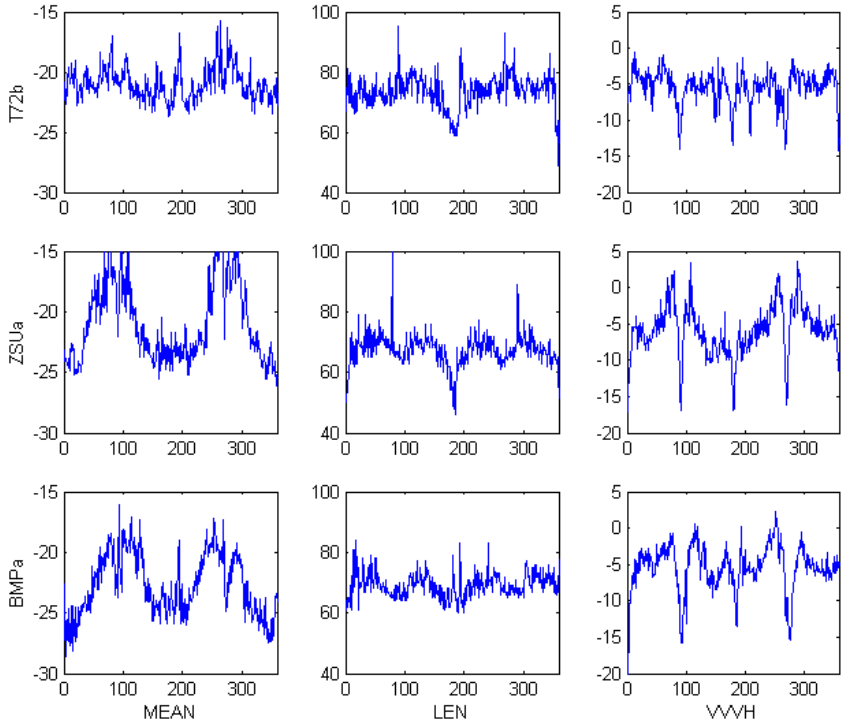

Figure 4. Feature MEAN, LEN and VVVH as a function of aspect angle for the three basic target modes.

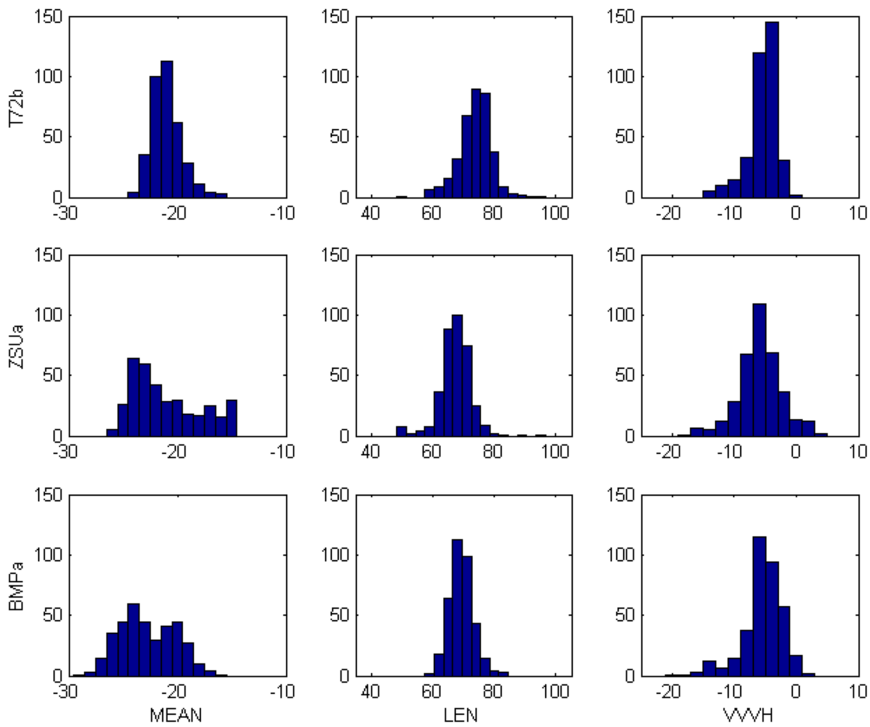

Figure 5. Feature distributions for MEAN, LEN and VVVH for the three basic target modes.

Figure 4 shows a large variability for feature MEAN as a function of aspect. Especially at 90 and 270 degrees of aspect, when the target is illuminated at the side bright scattering is seen when. Also the other two features show considerable variability as function of aspect, especially for aspect angle of 0, 90, 180 and 270 degrees, when the target is illuminated head-, side-, or tail-on. The variability will hamper the use of single features to discriminate between different kinds of targets (van den Broek at al., 2003). This is confirmed by the corresponding distributions in figure 5, which show considerably overlap between the three basic target modes for all three features.
In order to check the robustness against target modification we have taken the averaged value for the aspect angle interval 30-60 degrees for the features. For such aspect intervals features are relatively stable due to the absence of strong scattering which usually occurs when the target is illuminated head-, side-, or tail-on (van den Broek et al., 2003). We show in figure 6 histograms per target category for the features MEAN, LEN and VVVH.

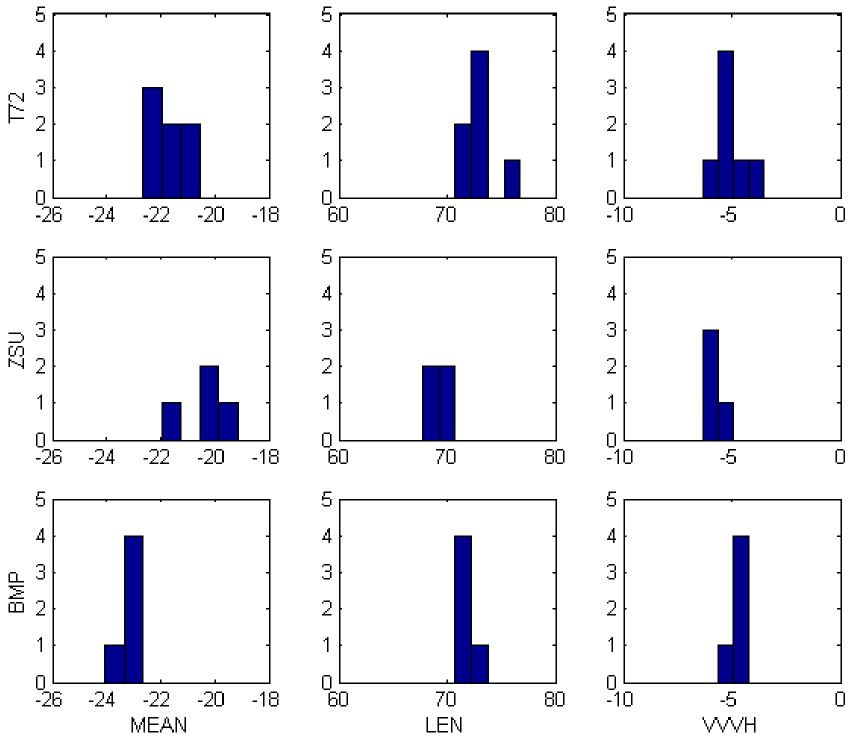

Figure 6. Distributions of target modes for features MEAN, LEN and VVHV in the aspect interval 30-60 degrees.

Figure 6 shows that the feature distributions of target modes in the 30-60 degree aspect interval also have considerable overlap, but also that separation is possible between the three kinds of targets for feature MEAN. The widths of distributions are small so that the features are relatively insensitive to target modification.
In order get a quantitative measure for the potential of single features to discriminate between targets we have calculated the Kolmogoroff-Smirnov distances (KSD) between distributions (Schimpf 2004). In table 3 we give the values for the KSD averaged over the various modifications for the three target classes.

Table 3 Kolmogoroff-Smirnov distances for the various features and the three target classes. The distances are averaged over the modifications

	MEAN			CVAR			WFR		
	T72	ZSU	BMP	T72	ZSU	BMP	T72	ZSU	BMP
T72	0.11	0.28	0.35	0.06	0.14	0.20	0.06	0.15	0.28
ZSU		0.08	0.24		0.06	0.14		0.05	0.14
BMP			0.08			0.06			0.05
	AREA			NN			LAC		
	T72	ZSU	BMP	T72	ZSU	BMP	T72	ZSU	BMP
T72	0.13	0.40	0.60	0.10	0.10	0.52	0.09	0.10	0.53
ZSU		0.14	0.23		0.09	0.51		0.08	0.53
BMP			0.10			0.08			0.09
	LEN			WID			VVVH		
	T72	ZSU	BMP	T72	ZSU	BMP	T72	ZSU	BMP
T72	0.11	0.55	0.42	0.26	0.30	0.24	0.09	0.15	0.14
ZSU		0.06	0.20		0.13	0.12		0.04	0.14
BMP			0.06			0.08			0.03

We give in table 3 the distances between the three target classes in 9 matrices corresponding to the 9 features defined in the previous section. The matrices in the table are symmetric since interchange of targets should not have an effect and therefore only the upper part of the table is filled for clarity. The diagonal elements are not zero since these are averages of the intra-class distances between the different modifications. The off-diagonal elements give the inter-class distances between the three target classes. In table 4 we give average intra- and inter-class distances for all features by averaging the diagonal and off-diagonal elements in table 3, respectively.

Table 4 Average KSD distances per feature

Feature	Average diagonal	Average off-diagonal
MEAN	0.09	0.29
CVAR	0.06	0.16
WFR	0.05	0.19
AREA	0.12	0.41
NN	0.09	0.38
LAC	0.09	0.39
LEN	0.08	0.39
WID	0.16	0.22
VVVH	0.05	0.14

No discrimination implies a KSD of zero and optimal discrimination is obtained when the KSD is one. In is clear from the table the intra-class distances are relatively small compared to the inter-class distances. This means that these features are not able to discriminate between target modifications. The potential for inter-class discrimination is clearly greater for geometrical features with exception of feature WID.

5.2 Feature vectors and feature space

It is clear from the previous section that single features are not very capable to discriminate between targets and target modification. This can be concluded from the relatively low values for the KSDs. In order to get better discrimination results we combine single features into feature vectors and consider the feature values for the different targets as multidimensional clusters in a multidimensional feature space where the dimension corresponds to the number of features used. We show here two examples of a two-dimensional case.

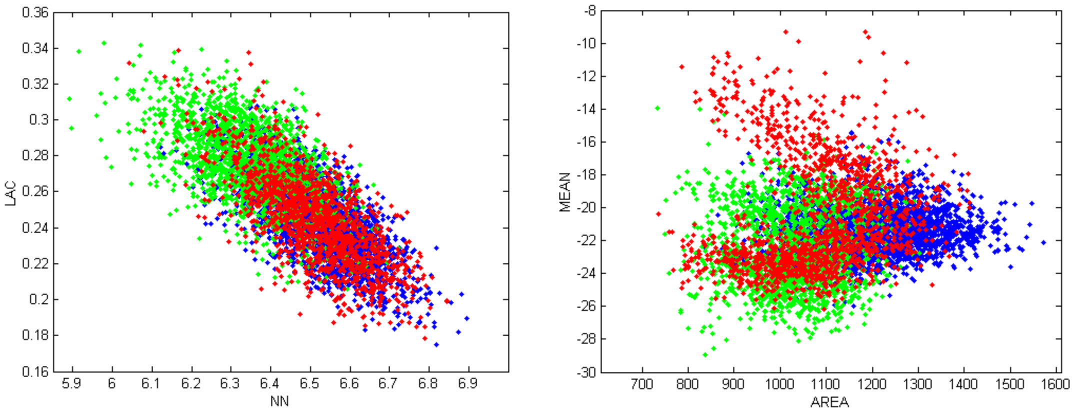

Figure 7. Scatter plot of feature NN against LAC (left) and feature MEAN against AREA (right) using all targets modifications and all aspect angles. Blue T72, green BMP and red ZSU.

In the first example of figure 7 we have plotted feature LAC against NN. The figure show that the clusters for the BMP and T72 can be separated quite well, but that the cluster for the ZSU overlaps mostly with the T72 cluster. The figure also shows that the features are correlated quite well. Obviously not all nine defined features are independent. When more features are used and the dimensionality increases the potential for discrimination usually increases. This is only the case when the features are independent and do not correlate like for feature NN and LAC. In that case the use of more features is less effective.
In the second example we plotted feature MEAN against AREA. Again the clusters for BMP and T72 are relatively separable, but the ZSU cluster shows overlap and a branch with high values for feature MEAN. To analyse this behaviour we have plotted the features NN and MEAN as a function of aspect angle in figure 8.

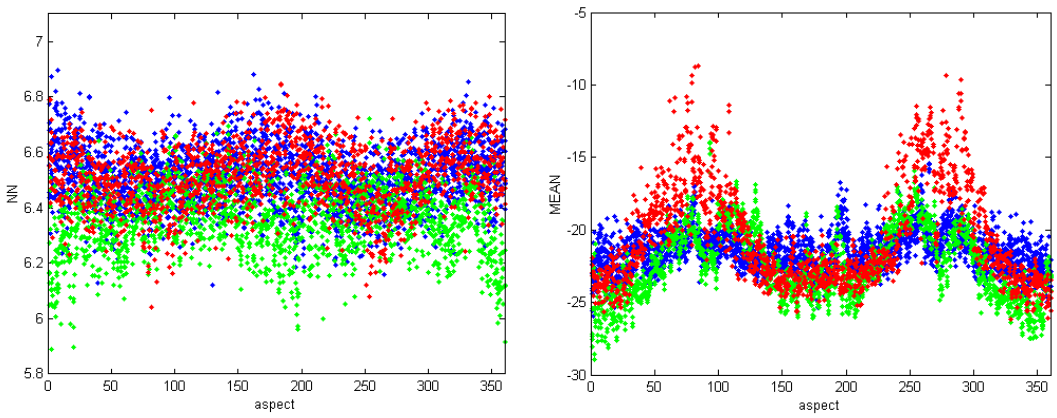

Figure 8. Scatter plot of feature NN (left) and feature MEAN (right) as a function of aspect. Blue T72, green BMP, and red ZSU where all modifications have been used.

Figure 8 shows that feature NN does not depend much on aspect angle contrary to feature AREA. Especially for the ZSU high values are found for aspect angles of 90 and 270 degrees (illumination of the side of the targets) which explains the branch in figure 7. The branch is present because high values are found in a relative small area. The way the CFAR mask is calculated (average backscatter level of the pixels in the target area) implies that the feature AREA will become smaller in case of intense compact backscatter.

In order study the potential for discrimination we consider the feature space with all values for the complete range of 360 aspect angles belonging to a particular target modification as a separate cluster. In a second step we classify each aspect angle and target modification on basis of these clusters. Various classification procedures exist, such as Mahalanobis distance, Support Vector Machines and the K-nearest neighbour. The first approach is parametric,

where the mean and the covariance matrix are used for each cluster. This method only works well when the clusters correspond to normal distributions. The latter two approaches are non-parametric approaches, which do require the clusters to be normal. The K-nearest neighbour method is quite straightforward, but has the disadvantage that for each vector the distance to all other vectors has to be calculated and is therefore rather computationally intensive. We use here the K-nearest neighbour classifier where we take K=10. This means that the majority of the 10 nearest neighbours determine the classification result.
After classifying all feature vectors belonging to an aspect angle and a target modification we can construct confusion matrices. The confusion is obtained by using the classifications for complete aspect angle range so that results become irrespective of aspect angle. In table 5 we show a confusion matrix where all 9 features defined in this paper have been used. The numbers in the confusion matrix are normalised such that the total of each row adds to 100.

Table 5 Confusion matrix for all target modifications and target classes

	T72							ZSU23-4				BMP				
	a	b	c	d	f	g	h	a	b	c	d	a	b	c	d	e
T72a	30	17	11	9	8	7	10	2	2	2	1	0	0	1	0	0
T72b	20	26	11	8	4	8	11	1	2	5	2	1	1	1	1	0
T72c	18	13	18	16	8	9	9	1	2	1	3	1	0	0	0	1
T72d	15	9	15	22	18	6	3	4	1	2	2	1	1	0	1	1
T72f	14	7	14	24	18	11	3	4	2	1	1	1	1	0	0	1
T72g	19	10	14	13	13	11	9	2	2	1	3	1	1	0	1	1
T72h	22	19	8	6	5	8	15	4	2	4	1	1	1	1	1	2
ZSU23-4a	4	3	4	6	6	3	4	22	21	14	9	1	1	0	1	1
ZSU23-4b	5	3	3	3	2	1	3	21	20	11	18	1	2	3	2	2
ZSU23-4c	6	5	3	3	3	2	6	25	15	13	16	1	0	0	1	1
ZSU23-4d	3	6	2	2	3	2	4	16	23	19	16	1	1	1	1	1
BMPa	0	1	2	1	0	2	1	2	3	1	1	24	22	20	11	10
BMPb	0	1	1	1	1	1	2	1	2	2	0	31	13	21	9	14
BMPc	0	1	0	1	0	1	2	1	3	0	1	22	19	15	21	14
BMPd	1	1	1	2	1	1	1	3	4	1	2	21	13	25	9	16
BMPe	1	1	1	3	2	1	1	1	3	2	1	21	14	21	18	10

In this table we discriminate between intra-class sections (dark grey shaded regions) en inter-class sections (light grey shaded and white regions). We will fist analyse the intra-class sections and then the inter-class sections.

<u>Intra-class analysis</u>
In case the measurements are not sensible to a modification we should find, a number of 100 divided by the number of modifications within each target class, for the intra-class sections in the matrix (complete confusion). This 'reference' number is given in the table 6 together with the actual average numbers for the diagonal and off-diagonal elements in the dark shaded intra-class areas. A number higher than the reference value means that the measurements are able to discriminate between modifications and consequently the off-diagonal numbers, which indicate the confusing, should be lower. Comparable diagonal and off-diagonal numbers indicate that the data are not capable to discriminate between modifications.

Table 6 Averaged intra-class values from dark grey shaded areas in table 5.

	Reference value	Average diagonal	Average off-diagonal
T72	14	20	11
ZSU23-4	25	18	17
BMP	20	14	18

As can be seen from table 6 the data appears to be able to discriminate between modifications of the T72 target to a certain extent, but not between modifications of the ZSU and BMP, since for the latter two cases diagonal and off-diagonal numbers are comparable. These numbers are somewhat lower than the reference value since there is also some confusion between the different target types (see inter-class analysis).

Inter-class analysis

In case the measurements are able to completely discriminate between three target classes we would expect zeros for the inter-class sections. This is mostly true since most values in the light grey and white section of table 5 are small. To study the inter-class confusion further we summarise in table 7 the average values for the intra-class and inter-class sections of the confusion matrix shown in table 5. In table 7 the numbers are normalised so that the total of each row is 100.

Table 7. Averaged intra- and inter-class values

	T72	ZSU23-4	BMP
T72	89	9	3
ZSU23-4	25	70	6
BMP	7	7	87

It is clear that discrimination between the target classes is quite well possible. Most confusion is found for the ZSU, which is sometimes classified as a T72. This is in agreement with figure 7 where the ZSU cluster shows most overlap with the T72 cluster.
Above results are obtained using all 9 features. Not all features will be completely independent, so that the effective number of independent features can be lower (see previous section). It is therefore interesting to inspect the results using a smaller number of features, which are obviously independent. We therefore use the most straightforward feature in the category radiometric (MEAN), geometric (AREA) and polarimetric (VVVH). In a 3-dimensional feature space using feature vectors consisting of MEAN, AREA, and VVVH we show the results in table 8 analogous to table 7.

Table 8. Average intra- and inter-class values using a sub-set of features (MEAN, AREA and VVVH).

	T72	ZSU23-4	BMP
T72	83	10	8
ZSU23-4	34	55	12
BMP	22	17	61

From the table it is clear that there is now substantially more confusion between the target classes, so that the conclusion is that a high number of features is desirable. For a high number of features, methods like principle component analysis can be used to obtain smaller sets of independent features, which are as effective.

5.3 Analysis per aspect interval

Since the aspect angle can be determined within 20 degrees accuracy using methods like the Radon transform (see above) we do not need to consider target discrimination using the complete aspect angle range, but can consider this in practice per aspect interval. We consider aspect intervals of 40 degrees and have calculated average values of correct classification from the main diagonal of the confusion matrices like are shown in table 7 and 8. This is done again for all 9 features and for the three features (MEAN, AREA and VVVH) used above. In figure 9 we show the average values of correction classification per 40-degree aspect interval as a function of aspect.

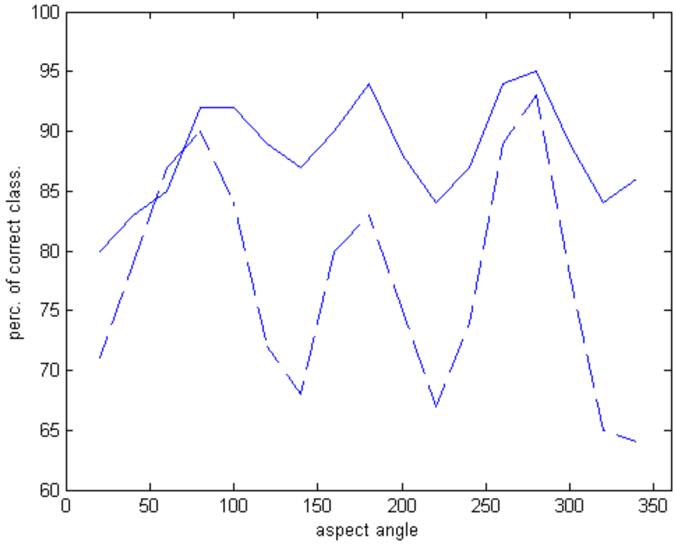

Figure 9. Percentages of correct classification as function aspect angle for the complete feature set (solid line) and a sub-set of features (dashed line)

The percentages of correct classification in figure 9 are substantially higher compared to the average values obtained from table 7 and 8 (82 and 66, respectively). This is true for all aspect angle intervals. Only for the aspect angles near 0, 140 and 220 degrees of aspect the results are somewhat comparable.

6. Summary and conclusions

We have studied a set of three target classes with several target modifications in each class. On basis of a set of features defined in this paper we obtained intra-class and inter-class classification results. These results show that single features are not very sensitive to target modifications but are rather dependent on the aspect angle. Single features are therefore not very useful to discriminate between different target classes. Analysis of multi-dimensional feature spaces using feature vectors composed of the various single features shows good results for inter-class target discrimination. These results can even be better when the analysis is done per aspect angle interval. This is possible in practice since the aspect angle can be determined effectively with methods like the Radon transformation. The use of feature vectors does not show substantially better results for discrimination between different target modifications. We therefore conclude that the features used here are rather robust against target modification and that for robustness against aspect angle features vectors consisting of a high number of single features has to be used in combination with aspect angle determination.

References

1. Broek, van den, A.C., Dekker, R.J., Steeghs, T.P.H., Robustness of Features for Automatic Target Discriminaton in High Resolution Polarimetric SAR Data, *Algorithms for Synthetic Aperture Radar Imagery X, Proc. of SPIE, Vol. 5095, 2003*, pp. 242-253.
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Target discrimination and robust features

TNO Defence, Security and Safety

TNO | Knowledge for business

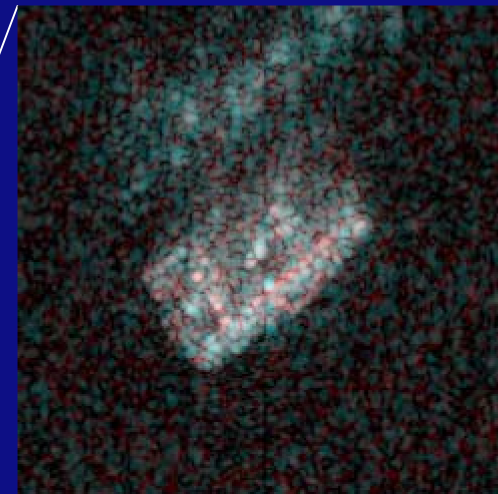
Bert van den Broek, Rob Dekker

Matrix Specialist Meeting
10-12 May 2005 Oberammergau

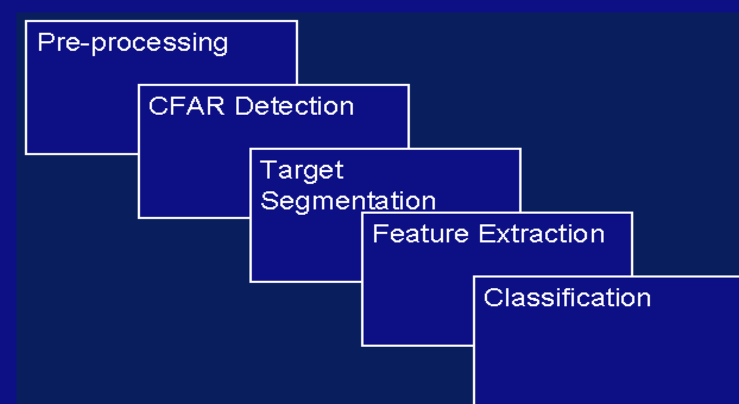
Outline

- Background
- Data & features
- Aspect angle
- Classification
- Analysis
- Summary

Processing & Interpretation



- feature enhanced processing
- pose estimation
- feature extraction
- criteria - classification



- target extraction
- change detection
- false alarm suppression
- target discrimination

Target ISAR data

- Modifications
- 360 aspect angles

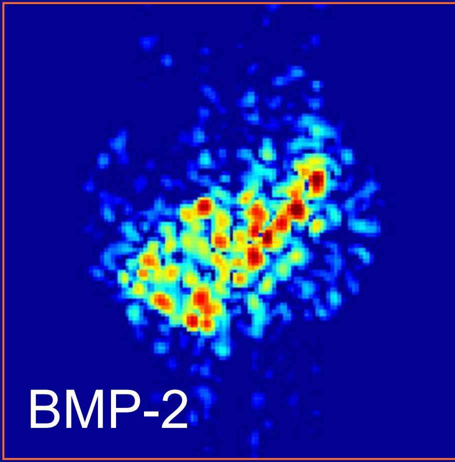
Ka-band (35 Ghz)

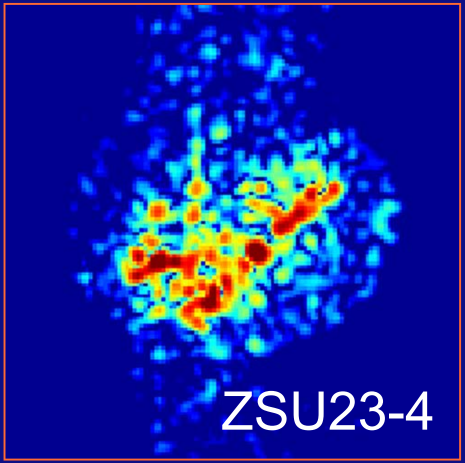
Images using:

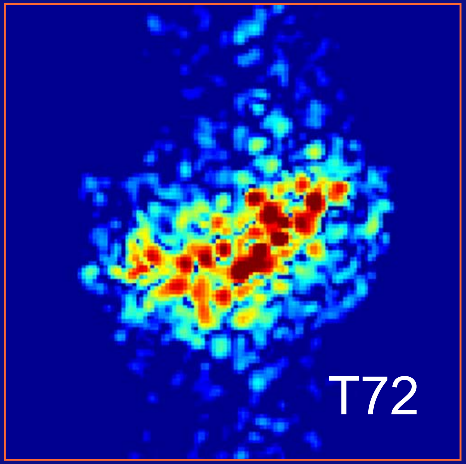
256 frequency steps
bandwidth 640 Mhz
0.24 cm range resolution
128 lines of 0.01 degrees
0.20 cm cross range resolution

Target ID	Modification	No. of range lines
T-72a	Gun –20° azimuth (left)	36963
T-72b	Gun 0° azimuth (forward)	37001
T-72c	Gun 30° azimuth (right)	36876
T-72d	Gun 60° azimuth (right)	36963
T-72f	Gun 120° azimuth (right)	37001
T-72g	Gun 150° azimuth (right)	37001
T-72h	Gun 180° azimuth (backward)	37013
ZSU 23-4a	driver's hatch closed, commander's hatch closed	36013
ZSU 23-4b	driver's hatch open, commander's hatch closed	35762
ZSU 23-4c	all hatches open	36013
ZSU 23-4d	driver's hatch closed, commander's hatch open	36013
BMPa	All hatches closed	37375
BMPb	driver's hatch open, commander's hatch closed	37375
BMPc	driver's hatch open, commander's hatch open	37375
BMPd	driver's hatch open, commander's hatch open, turret hatch open	37375
BMPe	driver's hatch closed, commander's hatch open, turret hatch open	37375

ISAR images of targets



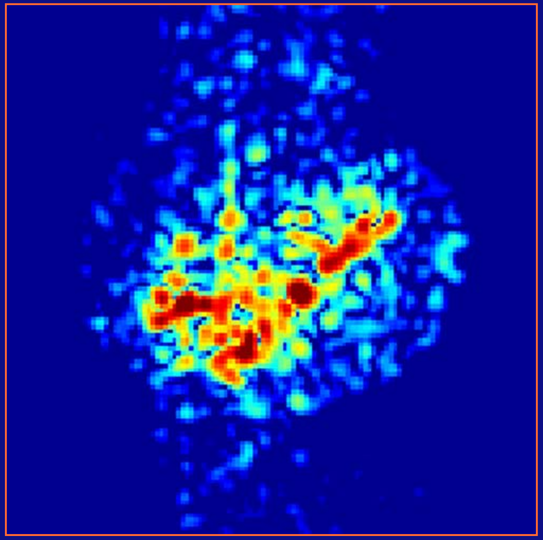




Features & CFAR mask

Aspect angle determination

Type	Feature	Description
Radiometric	*MEAN*	mean intensity
	CVAR	coefficient of variation
	WFR	weighted rank fill ratio
Geometric	*AREA*	area of target
	NN	neighbour number
	LAC	lacunarity index
	LEN	length of target
	WID	Width of target
Polarimetric	*VVVH*	polarimetric (VV/VH) power ratio

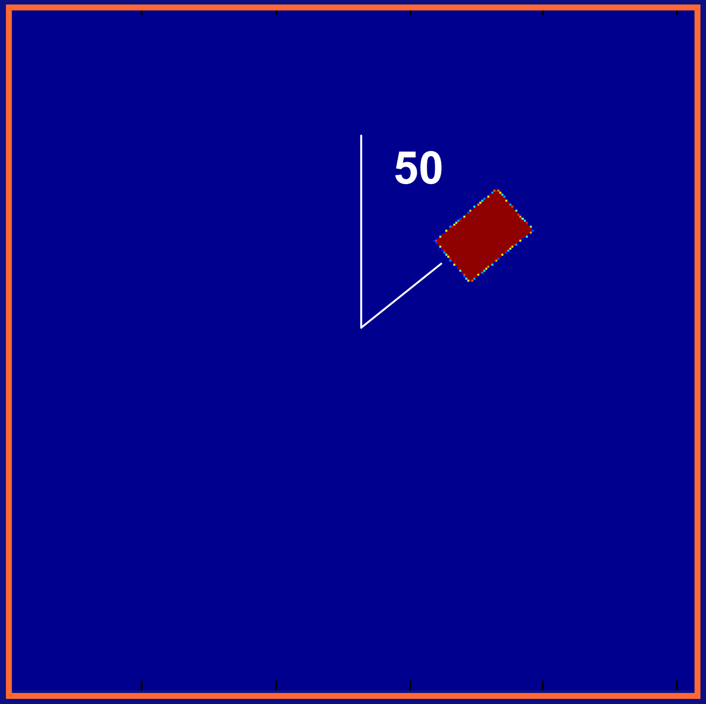


Features are based on CFAR mask

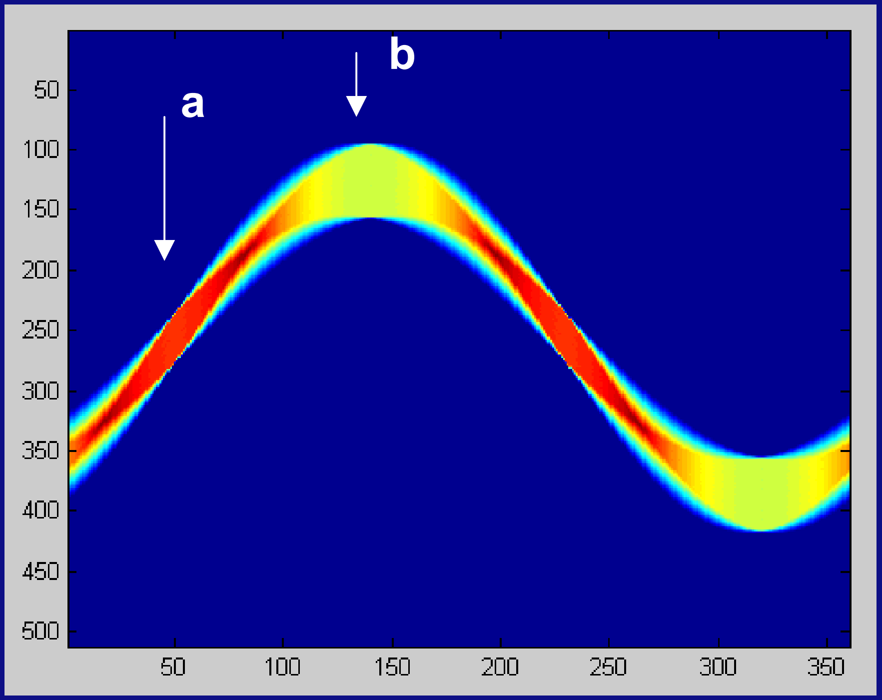
Aspect angle determination via ‘Radon’ transformation

a - bandwidth minimum, intensity maximum (short side, front/rear)
b - bandwidth maximum, intensity minimum (long side, sideways)

Target 50 deg. aspect



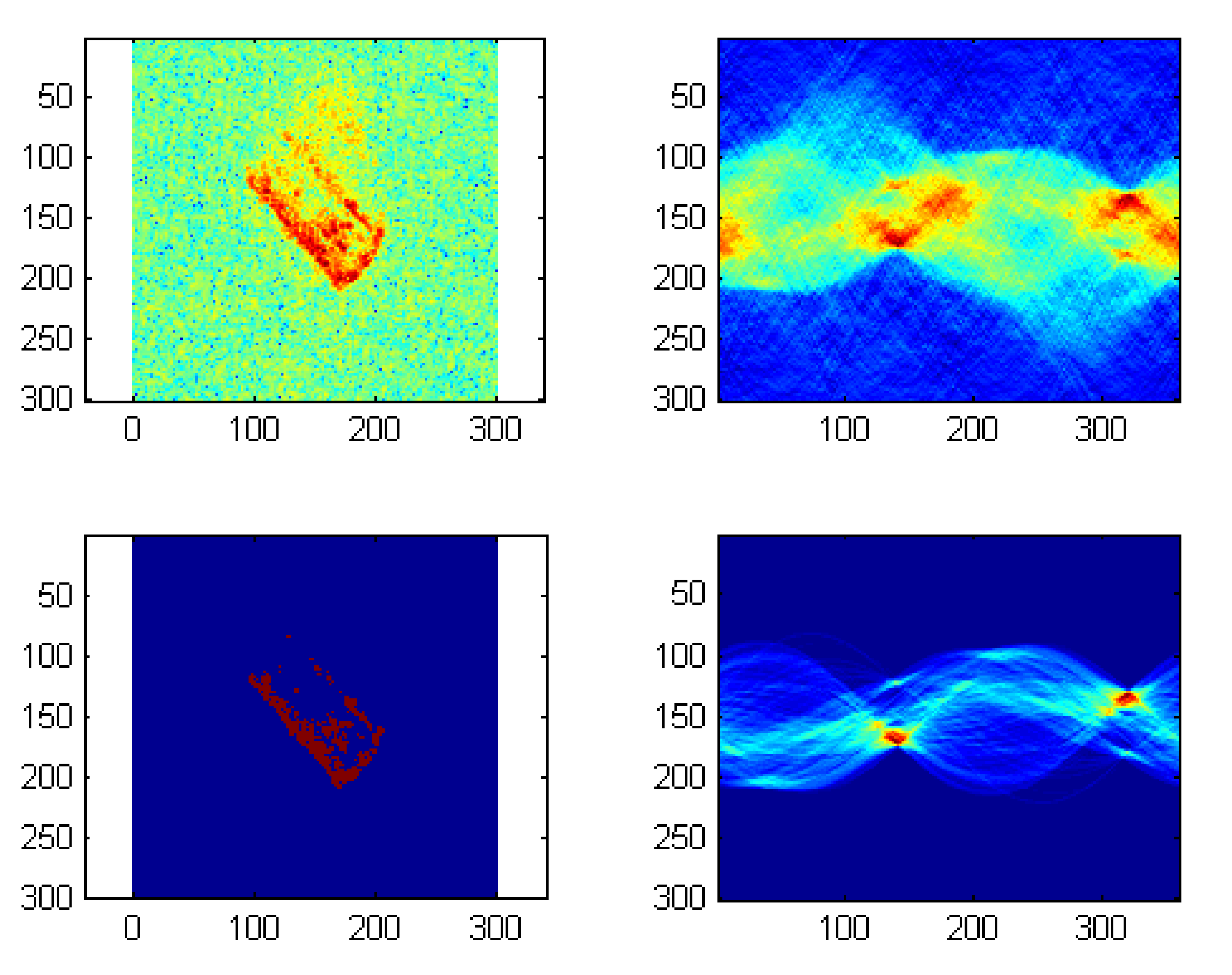
‘Radon’ image



CFAR mask & Radon transformation

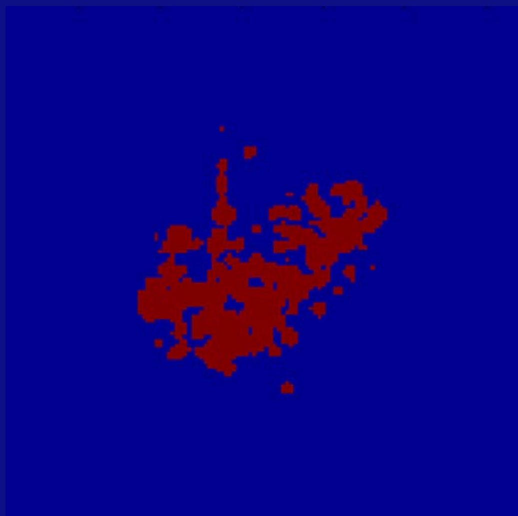
Image

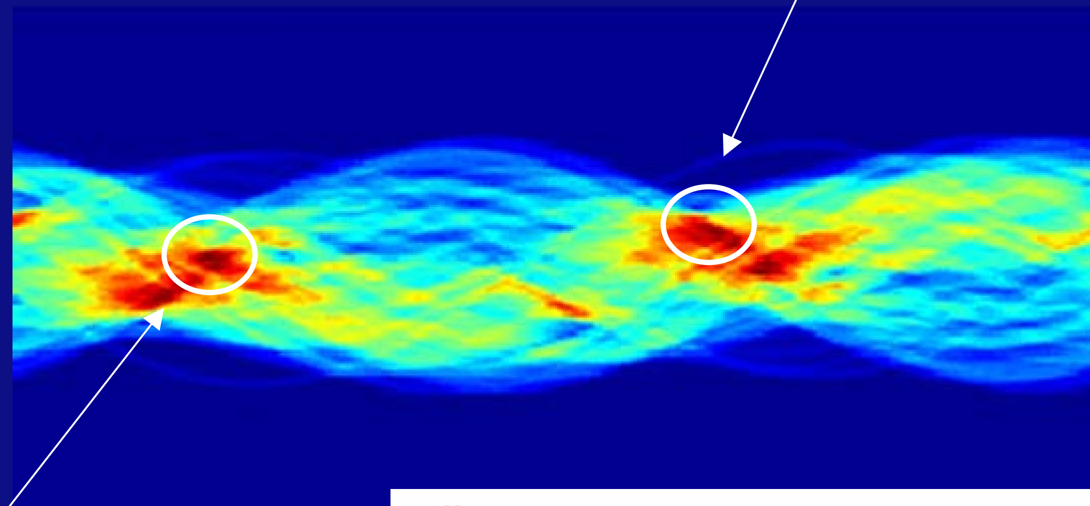
CFAR



Results Radon transformation

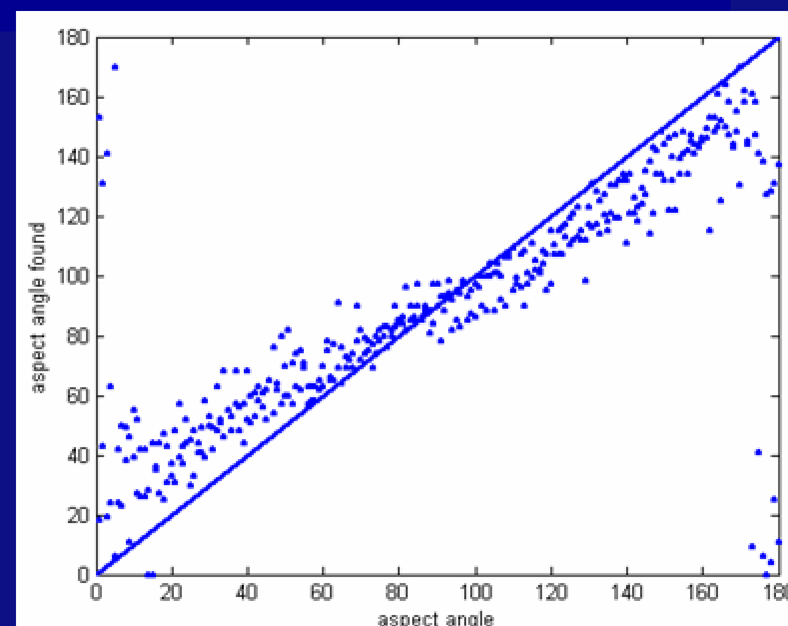
2nd maximum





1st maximum

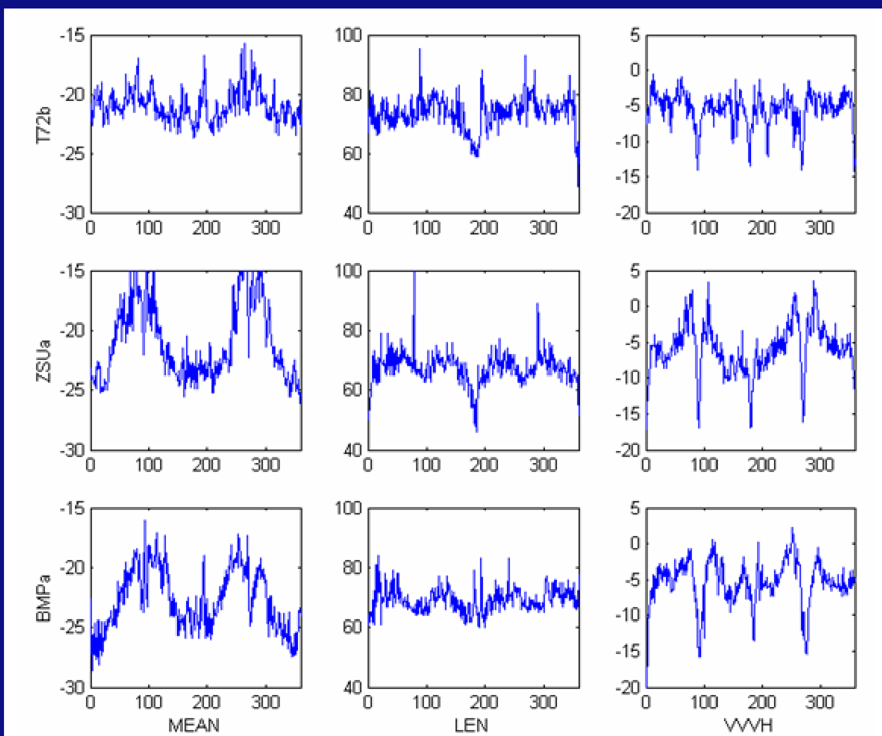
Accuracy about ± 20 deg.

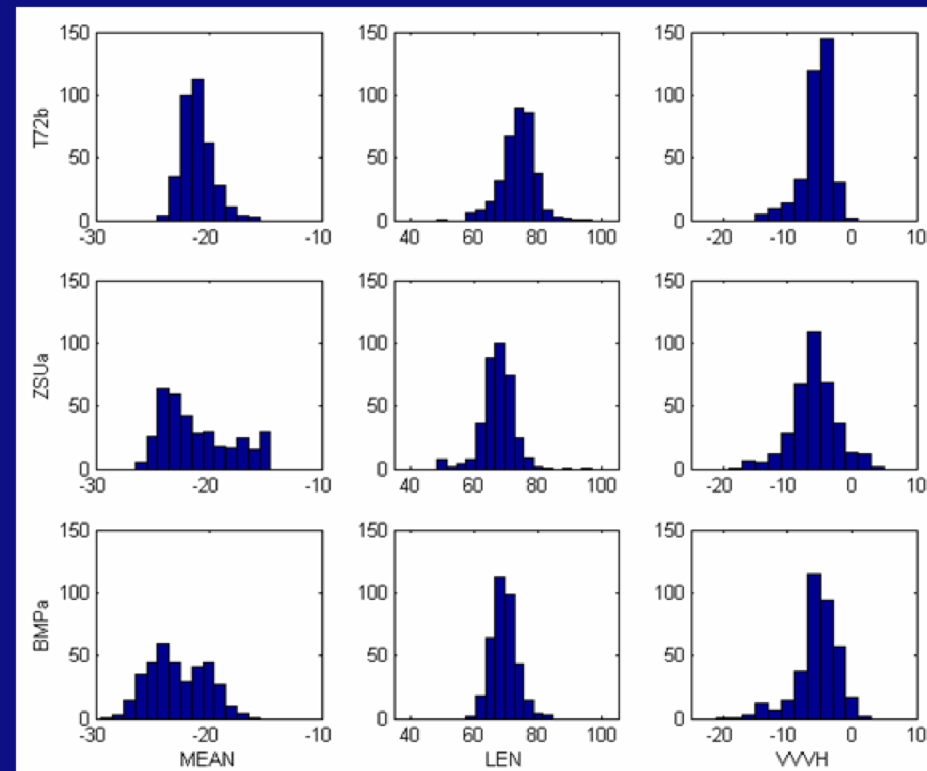


Features statistics
aspect angle

Basic target modes:
no modification

Feature distributions



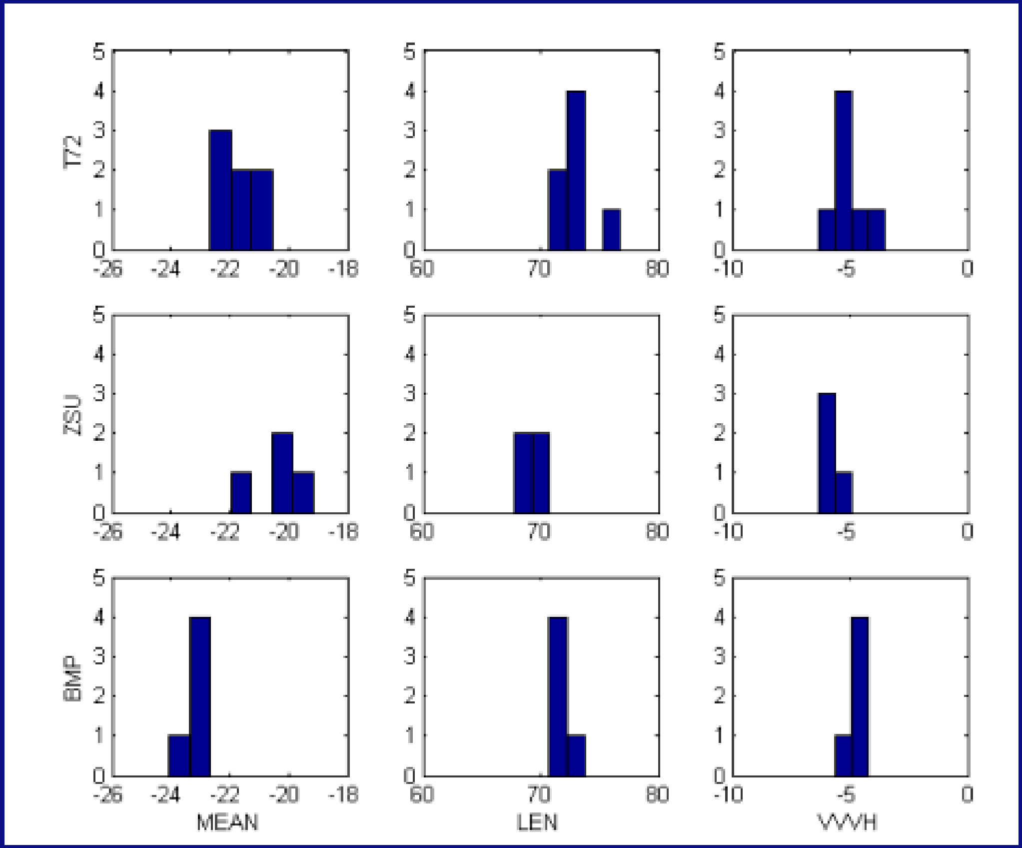


Feature as function of aspect angle

Features statistics
modifications

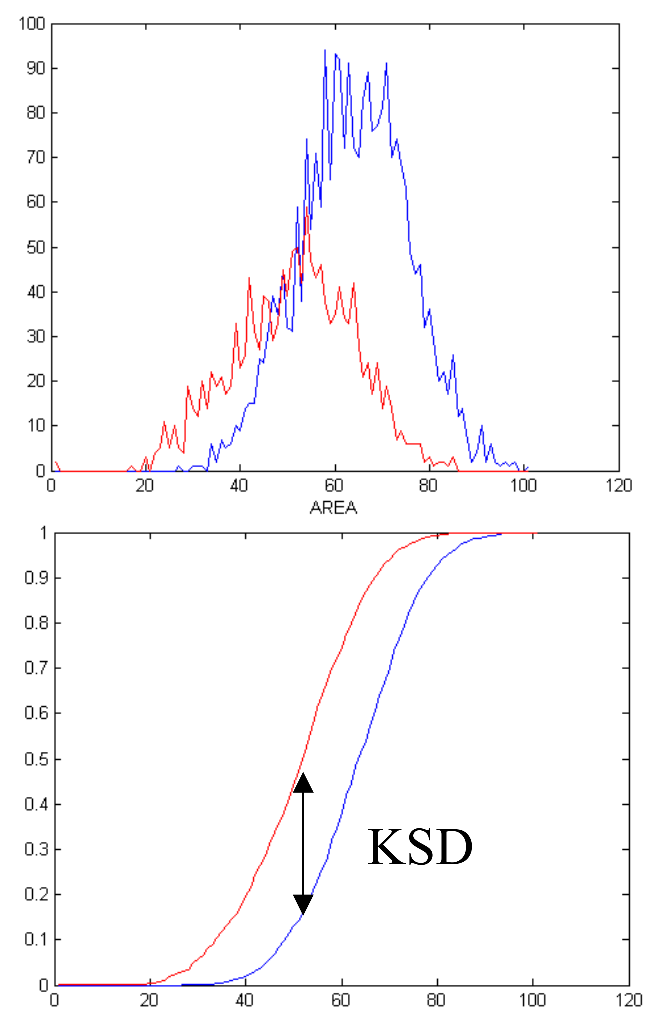
Fixed aspect angle interval:
30-60 degrees

Feature distributions



Feature separability

Kolmogoroff-Smirnov distance (KSD) between feature distributions
= max distance between cumulative distributions



KSD=0, distributions are identical

KSD=1, distributions are completely separable

Average Kolmogoroff-Smirnov distances

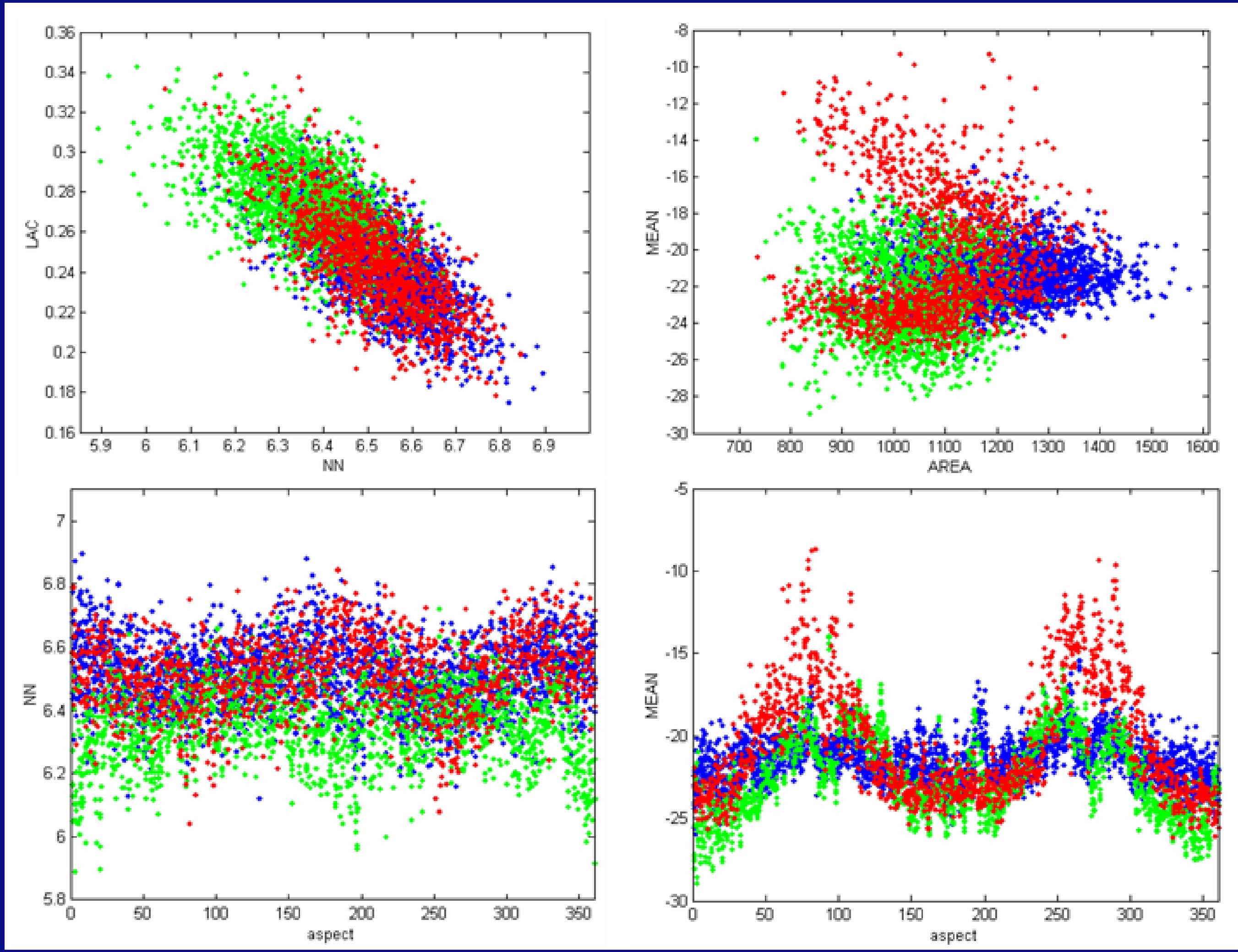
Feature	Average intra-class	Average Inter-class
MEAN	0.09	0.29
CVAR	0.06	0.16
WFR	0.05	0.19
AREA	0.12	0.41
NN	0.09	0.38
LAC	0.09	0.39
LEN	0.08	0.39
WID	0.16	0.22
VVVH	0.05	0.14

Feature distributions in feature space

Red: ZSU

Blue: T72

Green: BMP



Classification

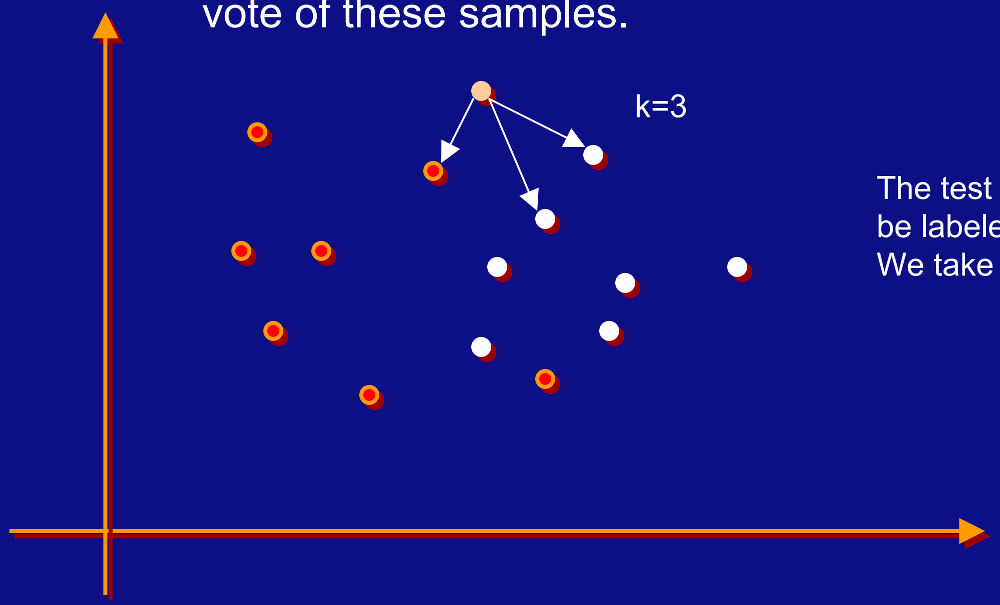
Parametric classification

e.g. Mahalanobis distance (for normal distributions)

Non-parametric classification

e.g. K-nearest-neighbour

The k-nearest-neighbour rule starts at the test point and grows until encloses k training samples, and it labels the test point by a majority vote of these samples.



The test point would be labeled as white.
We take K=10

Confusion matrix

Intra-class results

	T72							ZSU23-4				BMP				
	a	b	c	d	f	g	h	a	b	c	d	a	b	c	d	e
T72a	30	17	11	9	8	7	10	2	2	2	1	0	0	1	0	0
T72b	20	26	11	8	4	8	11	1	2	5	2	1	1	1	1	0
T72c	18	13	18	16	8	9	9	1	2	1	3	1	0	0	0	1
T72d	15	9	15	22	18	6	3	4	1	2	2	1	1	0	1	1
T72f	14	7	14	24	18	11	3	4	2	1	1	1	1	0	0	1
T72g	19	10	14	13	13	11	9	2	2	1	3	1	1	0	1	1
T72h	22	19	8	6	5	8	15	4	2	4	1	1	1	1	1	2
ZSU23-4a	4	3	4	6	6	3	4	22	21	14	9	1	1	0	1	1
ZSU23-4b	5	3	3	3	2	1	3	21	20	11	18	1	2	3	2	2
ZSU23-4c	6	5	3	3	3	2	6	25	15	13	16	1	0	0	1	1
ZSU23-4d	3	6	2	2	3	2	4	16	23	19	16	1	1	1	1	1
BMPa	0	1	2	1	0	2	1	2	3	1	1	24	22	20	11	10
BMPb	0	1	1	1	1	1	2	1	2	2	0	31	13	21	9	14
BMPc	0	1	0	1	0	1	2	1	3	0	1	22	19	15	21	14
BMPd	1	1	1	2	1	1	1	3	4	1	2	21	13	25	9	16
BMPe	1	1	1	3	2	1	1	1	3	2	1	21	14	21	18	10

Inter-class results

All nine features used

Intra-class analysis

	T72							ZSU23-4				BMP				
	a	b	c	d	f	g	h	a	b	c	d	a	b	c	d	e
T72a	30	17	11	9	8	7	10	2	2	2	1	0	0	1	0	0
T72b	20	26	11	8	4	8	11	1	2	5	2	1	1	1	1	0
T72c	18	13	18	16	8	9	9	1	2	1	3	1	0	0	0	1
T72d	15	9	15	22	18	6	3	4	1	2	2	1	1	0	1	1
T72f	14	7	14	24	18	11	3	4	2	1	1	1	1	0	0	1
T72g	19	10	14	13	13	11	9	2	2	1	3	1	1	0	1	1
T72h	22	19	8	6	5	8	15	4	2	4	1	1	1	1	1	2
ZSU23-4a	4	3	4	6	6	3	4	22	21	14	9	1	1	0	1	1
ZSU23-4b	5	3	3	3	2	1	3	21	20	11	18	1	2	3	2	2
ZSU23-4c	6	5	3	3	3	2	6	25	15	13	16	1	0	0	1	1
ZSU23-4d	3	6	2	2	3	2	4	16	23	19	16	1	1	1	1	1
BMPa	0	1	2	1	0	2	1	2	3	1	1	24	22	20	11	10
BMPb	0	1	1	1	1	1	2	1	2	2	0	31	13	21	9	14
BMPc	0	1	0	1	0	1	2	1	3	0	1	22	19	15	21	14
BMPd	1	1	1	2	1	1	1	3	4	1	2	21	13	25	9	16
BMPe	1	1	1	3	2	1	1	1	3	2	1	21	14	21	18	10

All nine features used

	Reference value	Average diagonal	Average off-diagonal
T72	14	20	11
ZSU23-4	25	18	17
BMP	20	14	18

Reference value for complete intra-class and no inter-class confusion = 100/(no. of mod.)

Inter-class analysis

	T72							ZSU23-4				BMP				
	a	b	c	d	f	g	h	a	b	c	d	a	b	c	d	e
T72a	30	17	11	9	8	7	10	2	2	2	1	0	0	1	0	0
T72b	20	26	11	8	4	8	11	1	2	5	2	1	1	1	1	0
T72c	18	13	18	16	8	9	9	1	2	1	3	1	0	0	0	1
T72d	15	9	15	22	18	6	3	4	1	2	2	1	1	0	1	1
T72f	14	7	14	24	18	11	3	4	2	1	1	1	1	0	0	1
T72g	19	10	14	13	13	11	9	2	2	1	3	1	1	0	1	1
T72h	22	19	8	6	5	8	15	4	2	4	1	1	1	1	1	2
ZSU23-4a	4	3	4	6	6	3	4	22	21	14	9	1	1	0	1	1
ZSU23-4b	5	3	3	3	2	1	3	21	20	11	18	1	2	3	2	2
ZSU23-4c	6	5	3	3	3	2	6	25	15	13	16	1	0	0	1	1
ZSU23-4d	3	6	2	2	3	2	4	16	23	19	16	1	1	1	1	1
BMPa	0	1	2	1	0	2	1	2	3	1	1	24	22	20	11	10
BMPb	0	1	1	1	1	1	2	1	2	2	0	31	13	21	9	14
BMPc	0	1	0	1	0	1	2	1	3	0	1	22	19	15	21	14
BMPd	1	1	1	2	1	1	1	3	4	1	2	21	13	25	9	16
BMPe	1	1	1	3	2	1	1	1	3	2	1	21	14	21	18	10

All nine features used

	T72	ZSU23-4	BMP
T72	89	9	3
ZSU23-4	25	70	6
BMP	7	7	87

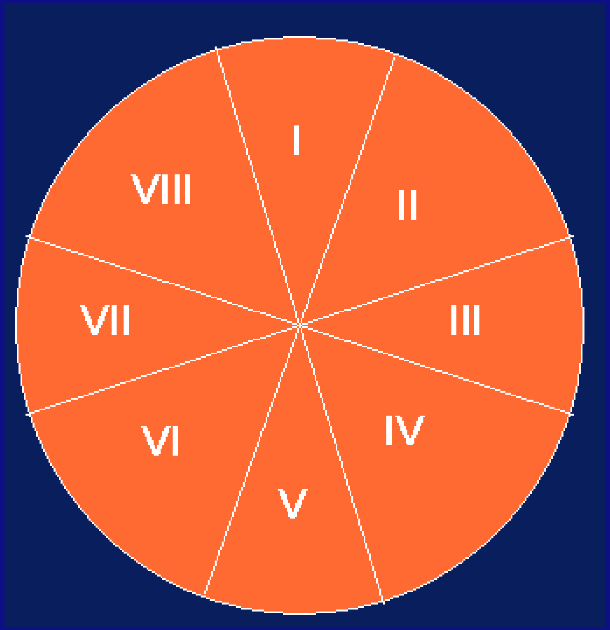
Data are normalised

Only feature MEAN, AREA &VVVH used

	T72	ZSU23-4	BMP
T72	83	10	8
ZSU23-4	34	55	12
BMP	22	17	61

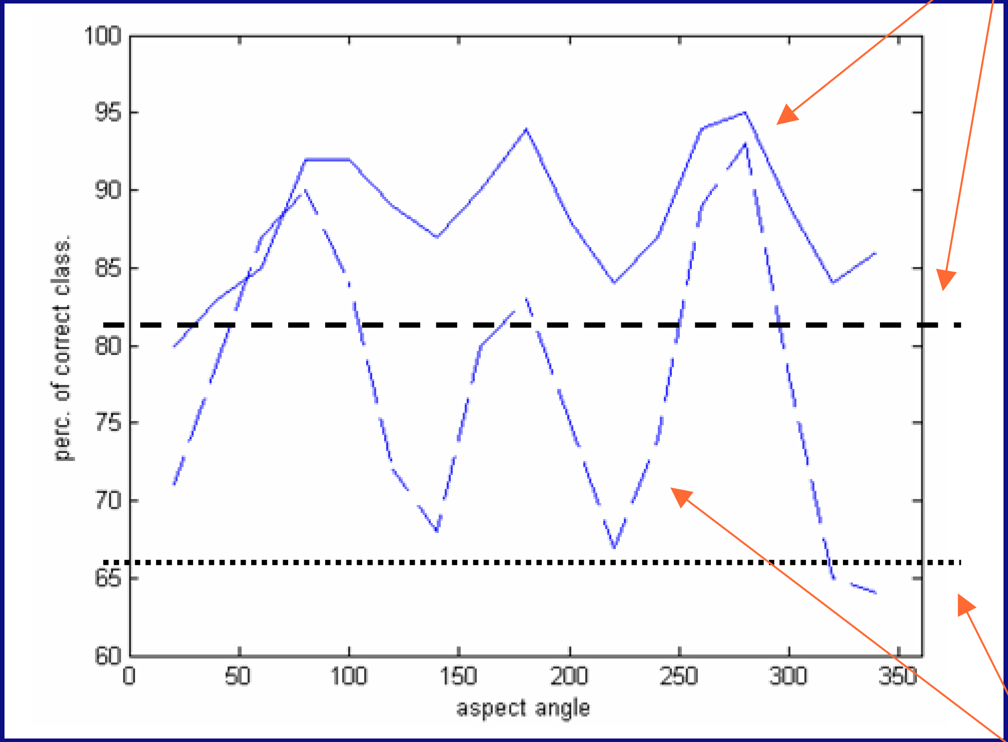
Discrimination per aspect angle interval

results improve significantly



Aspect angle intervals of for example 45 degrees

9 features used



3 features used

Summary

- Features show a strong dependence on aspect angle
- Therefore target discrimination with a single feature does not give good results
- Features are not sensitive to target modification
- Therefore intra-class target discrimination is not possible with features
- Multi-dimensional feature vectors give good inter-class discrimination
- Aspect angle determination possible with Radon transformation (accuracy of 20 deg).
- Inter-class discrimination per aspect interval improves the results